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(Plate 15).

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Introduction.

The conspicuous development of garnetiferous rocks in the metamorphic aureole of the Leinster Granite has been discussed by a number of authors. Sollas (1891) drew attention to such types in his description of a tiny fragment of siliceous garnet-hornfels from Carrickmines*, in which he shows the garnet to be essentially spessartine-almandine with composition Mn_{40} Fe_{40} Mg_{10} Ca_{10}: he suggested that it was the product of thermal metamorphism on a Lower Palaeozoic manganese-bearing slate comparable to types known in the Ordovician of Wales. Subsequently, Thompson (1908) described and figured siliceous garnet-hornfels bands from the contact zone of the ultra-basic mass on Camaderry Mountain. The general question of the occurrence of garnet in metamorphic aureole rocks is further discussed by Tilley (1926) with particular reference to the Leinster area—he suggests that a critical part was played by the manganiferous composition of the material—and these views are repeated by Harker (1939, p. 54).

Nevertheless, the widespread and persistent development of psammitic rocks rich in manganiferous garnet, and evidently of distinctive sedimentary composition, along the east flank of the Wicklow mass has so far passed unnoticed. It is the purpose of the present communication, firstly, to draw attention to these types and their characters, and secondly, to describe the peculiar small-scale structures which are associated with them to a remarkable degree.

Field Distribution.

The garnetiferous rocks are present as thin bands in the aureole schists on the eastern side of the Leinster mass, and extend from its northern end at least as far south as Glenmalure, a distance of some twenty-five miles: in spite of careful

* The specimen described was a minute piece, obtained at second-hand, so that its exact locality could not be confirmed. Since Carrickmines lies about two miles inside the granite boundary, and has no known schist exposures, it is considered most probable that the locality given is in error, and that the material likely came from one of the numerous garnetiferous bands at Rathmichael, due east of this point.

mapping they have not been detected on the western flank in the corresponding area. Outside the metamorphic aureole their representatives are so far unknown, nor have the distinctive ribbon-like folds been elsewhere observed.

At Killiney, where only a limited thickness of the aureole schists is exposed, typical garnetiferous beds have not been detected in spite of careful examination of the ground. Passing southwards, in the next group of outcrops at Rathmichael the beds are well-developed throughout the aureole, and show elaborate fold patterns; they continue by Ballycorus towards the Scalp and Enniskerry, but the restricted contact sections at the two latter localities have not, so far, provided examples. At Knockree, some two miles distant, the distinctive folded grits are again exposed and can be traced over the eastern slopes of Mount Maulin.

Above Powerscourt Waterfall, elegantly folded ribbons of the garnetiferous rock are seen, and from this point southwards they appear continually over Douce Mountain and by Luggala to Lough Dan, with everywhere the typical features and fold forms. In Glenmacnass they are again present and similarly are finely displayed in the Glendasan and Glendalough valleys. At Glenmalure are seen the most southerly outcrops so far examined.

Description of the Garnetiferous Beds.

The aureole rocks of the Leinster Granite are a series of Lower Palaeozoic sediments of geosynclinal facies, predominantly argillaceous in composition and without well-marked lithological subdivisions. Impure quartzites—the grit bands of the Survey workers—are present generally as thin intercalations: they only occasionally exceed a foot in thickness, though local siliceous groups of this nature may range up to 15-20 feet, as, for example, at Powerscourt. While a full Ordovician succession from Arenig to Bala is present further south in the Lower Palaeozoic massif (Hallissy, 1939, p. 294) the precise age of these aureole schists is unknown: they are generally referred to the Ordovician on the evidence of Bala fossils in the slates near Rathdrum, some six miles across strike from Glenmalure.

While garnet occurs generally as a normal contact-metamorphic product in the common muscovite-schist types, its striking and unusual development is in connection with the psammitic bands in the series. These richly garnetiferous types appear as thin and remarkably persistent layers, ranging from a millimeter or two to as much as fifty millimeters in thickness, and individually continuing as far as the limits of the exposures permit their observation. At some localities they are present throughout the extent of the aureole as intercalations in the mica-schists, and tend to occur in local, regular, closely spaced groups which would represent primary lithological units of the nature of thin-bedded psammitic-pelitic alternations (Plate 14 A). The most striking general character of these bands is their remarkable uniformity in composition and texture, and it is considered, therefore, that they are primary stratification layers which represent essentially the original composition of the material.

In hand specimen the typical garnetiferous variety is a dull grey or black rock, often stained on fracture surfaces in a rather characteristic manner by ferro-manganese oxides. Of even texture and crowded with minute garnets of a dark grey colour, it sometimes—in the case of the thicker layers—shows an internal banding, marked by paler and darker portions, where quartz and garnet respectively predominate. Among the more coarsely crystalline metamorphic products in the inner part of the aureole the bands tend to assume a pale reddish colour, with the translucent garnets showing very pale pink tints and scarcely distinguishable from the quartzose ground-mass of the rock. The scattered crystals of the mineral in the normal aureole schists are of larger dimensions than in these occurrences and have the common wine-coloured appearance.

Microscopically (Plate 15 D) the bands are found to be composed of garnet and quartz as the major constituents, the former ranging from 44 to 55 per cent of the rock according to micrometric analyses of typical bands. The garnet is present in rounded, equidimensional grains and granular clusters, seldom with a definite body colour or the characteristic fracture cracks, but contrasting with the surrounding quartz grains chiefly by their clouded appearance due to a fine dust of opaque inclusions. Quartz is the only other major constituent, and occurs in grains considerably smaller in size and with simple interlocking boundaries: it only rarely appears enclosed within the garnet. Scattered plates of pale-green chlorite are present in minor amounts, essentially from the alteration of high-grade biotite, and in some places muscovite also similarly occurs: felspar has been noted in some occurrences (Sollas, 1891). The chief accessory mineral is a dust of fine opaque grains—present in both garnet and quartz with a marked tendency to aggregate in moss-like forms, and apparently composed of iron and manganese oxides. At the margins of the band a few larger scales of ilmenite are also present in association with the muscovite fabric of the adjoining schist. Primary sedimentary textures, other than the stratification features mentioned above, are absent in the totally recrystallised material, but a divergent radial structure is sometimes noticeable: arranged perpendicular to the arches of small-scale folds it represents a system of tension cracks developed by stretching of the bed during bending and later filled-in by clear quartz mosaic (Pl. 15 C).

Towards the margins of the garnetiferous bands progressive changes in texture are seen, and the garnets appear conspicuously larger and idioblastic, and scattered more widely apart in the quartz mosaic, though their actual volumetric proportions remain more or less unchanged. The amount of opaque dust present in both of the major constituents is also much reduced, these minerals having cleared themselves during growth of much of the inert material. The ore particles often appear crowded along the sutures of the quartz mosaic, and within the garnets show a well-developed zonary distribution in special geometrical patterns (c.f. Harker, 1939, Fig. 8 c). Such effects clearly indicate the increasing efficiency of metamorphic diffusion towards the margins of the garnetiferous layer. In hand

specimen the boundaries of the layers are unusually distinct for a recrystallised rock, and break apart at the junction with smooth surfaces. Microscopically they are marked by a rather abrupt transition from the quartz mosaic to the aligned mica fabric of the adjacent schist, though it is frequently observed that the garnets occur profusely in the schist for some distance beyond the actual stratification boundary (Pl. 15 B & C).

The normal psammitic rocks of the aureole are fine-grained grey quartzites with typical mosaic texture. Biotite, or its alteration product chlorite, is present in scattered plates aligned to the general banding, and with increase in this constituent and appearance of the other characteristic metamorphic silicates, the types pass over through siliceous biotite-hornfels to the prevalent mica-schist. Varieties containing notable amounts of garnet, and forming a transition to the garnetiferous rocks proper, are also present, but, on the whole, the latter types are notably distinctive in their occurrence both in the field and in hand-specimen: they sometimes appear as garnet-rich layers interbanded in the normal quartzites. Segregation lenses and lenticular veins of coarsely-sutured quartz grains are developed concordantly to the structure of the rock, and frequently show replacement relations to their surroundings; as minor segregation features small clustered masses of pale rose-coloured garnets are locally present in association with these.

Subsequent in development to the garnetiferous quartzites, cross-cutting aplites and quartz-felspar veins are locally apparent, and an intense tourmalinisation is present at many places (Metamorphic Stage 2. Brindley, 1948): these features serve to date the formation of the associated fold structures in the general metamorphic history. The latter type of action is particularly pronounced in the intervening schist, so that the garnetiferous layers, with their already-formed ribbon folds, often appear prominently outlined in dark tourmaline-rich surroundings. In a still later metamorphic stage (Stage 3. *op. cit.*) deformation effects have produced widespread contortion of the aureole schists, accompanied by break-down of their high-grade metamorphic minerals. Such features appear commonly in the nature of an irregular crumpling superimposed on the tightly folded ribbons (Pl. 14 A, Fig. 1 A), and are accompanied by alteration of their garnets to chloritic pseudomorphs.

Discussion of Mode of Origin.

It is seen from the foregoing description that the garnetiferous layers are in the nature of thin intercalated strata in the Lower Palaeozoic geosynclinal sediments of Wicklow: they represent persistently developed sedimentary ironstone beds carrying notable proportions of manganese. Sedimentary iron and manganese deposits of marine origin are of wide distribution as minor types. In North Wales such rocks are found in both Cambrian and Ordovician systems, and have in fact provided low grade ferro-manganese ores. The main occurrences are carbonatic rocks with siderite and dialogite in their composition, as well as iron silicate minerals such as chamosite, and iron and manganese oxides. Carbonate-free chamositic mud-

stones also occur, however, and in the comparable Ordovician ironstones of Schmiedefeld in Saxony such siliceous types are present along with the more important carbonate-bearing strata (Zalinski, 1904).

In the Wicklow Lower Palaeozoics, however, carbonate sediments are essentially absent. The garnetiferous rocks here are mineralogically similar to some of the low-grade metamorphic derivatives of the Welsh sedimentary manganese rocks. Woodland (1938, 1939) has described, as minor types among the carbonate ores, quartz-spessartine rocks carrying up to 90% of the latter mineral from the mines of Hendre and Cwm Mawr, which are esssentially similar in character to this material. Local occurrences of spessartine-magnetite rock are also described and illustrated by H. Williams (1927, p. 360) and D. Williams (1930, p. 201) from the Snowdonian Ordovician, and considered by them to represent the metamorphic products of a manganese-bearing sediment. Another notable occurrence is in the Irish Lower Palaeozoics of counties Cavan and Longford (Hull, 1872) where compact siliceous hematites passing to jaspery rocks—apparently interbedded as sedimentary strata—are traceable along strike for several miles. This is clearly an oxide ore, with over 57% of iron oxide and some 6% of manganese, and in the past several thousand tons have been mined: the material contains some 22% of silica, and is essentially free from carbonate.

It will be seen from analyses of the Wicklow material (Table 1) that the composition compares very closely with that of Sollas' specimen (Sollas, 1891, p. 48), and corresponds generally to the observed mineral composition of these rocks.

TABLE 1.

A		B	
SiO_2	47·47	SiO_2	51·9
Al_2O_3	20·46	Al_2O_3	12·0
FeO	10·22	FeO	11·1
Fe_2O_3	Traces	MnO	8·6
TiO_2	0·52	CaO	3·5
MnO	9·03	MgO	6·1
CaO	3·02	H_2O	3·0
MgO	2·48		
K_2O	0·54		
Na_2O	2·64		
H_2O up to 105° C	0·09		
H_2O above 105° C	1·82		
CO_2	Nil		
P_2O_5	0·48		
Carbon	1·16		
	99·93		

A. Specimen of dark quartz-garnet rock from Glendasan Valley, Co. Wicklow. Analyst, W. H. Herdsman.

B. Partial analysis of specimen of similar material, Glendalough, Co. Wicklow. Analysed by Dr. A. G. G. Leonard.

It indicates a garnet of almandine-spessartine composition, in which minor amounts of lime and magnesia are evidently associated in isomorphous fashion. Carbonate

is notably absent in all the analyses, and the considerable amounts of alumina present would suggest an iron silicate mineral in the original sediment. Among modern sedimentary types a glauconitic sand would perhaps provide the closest analogy both in composition and setting, though such rocks are not usually associated with notable amounts of manganese.

Small-scale Fold Structures.

We now come to examine the peculiar minor structures so generally and profusely developed in the garnetiferous layers along the eastern flank of the granite mass. These are compressed ribbon-like folds of extreme complexity (Pl. 15 A) which were developed during the main contact-metamorphism (Metamorphic Stage 1) of the rocks. The beds affected vary in size from about 15mm. down to very small thicknesses, and thicker layers—chiefly those of normal quartzitic character—show a different style of deformation. Age relationships of the compressed folds are clearly indicated by the controlling influence of the paracrystalline schistosity of the surrounding Killiney-type mica-schists on their formation, and it will be shown that they have been developed by disharmonic movement effects between siliceous bands and schists. Likewise, features of Metamorphic Stages 2 and 3 in the aureole history are locally superimposed on the compressed folds subsequent to their formation (see above p. 248), and buckling effects due to later deformation of the rocks clearly post-date their formation.

The folds exhibit highly variable pitch relations of their individual members, and are seen to differ widely among themselves in orientation. In general terms, however, they correspond in arrangement throughout the district to other mechanical and paracrystalline structures developed in the same period of deformation—other fold structures, contorted veins, and segregation lenses: this orientation is clearly exhibited at several localities (e.g., The Scalp and Glenmalure). In the outcrop they commonly lie at an angle on schistosity surfaces, and thus oblique to the main structural trend of the region.

The predominant and most striking characteristic of the compressed folds is their relation to the schistosity of the surrounding pelites, and on this basis they fall into two main groups. In the first class the structures lie flat on—and directed parallel to—the trend of the psammitic layer involved, and are smoothly enclosed by the surrounding schistosity, which likewise corresponds to this direction (Fig. 1 C & D). In other words, stratification and schistosity run parallel to each other. In this way they commonly appear as separated node-like bodies in the schist, each showing internally a compacted cluster of folds of one garnetiferous layer connected together by the intervening unfolded portions of the band. Such pod-like masses are often prominent as loose fragments in the débris associated with outcrops of the garnetiferous beds, and have provided several of the examples illustrated in this paper. In other cases (e.g., Fig. 1 C & D) a regular spacing and arrangement of single compressed minor folds along a band suggests that their original development may have been as normal drag-fold structures on the flank of a larger fold.

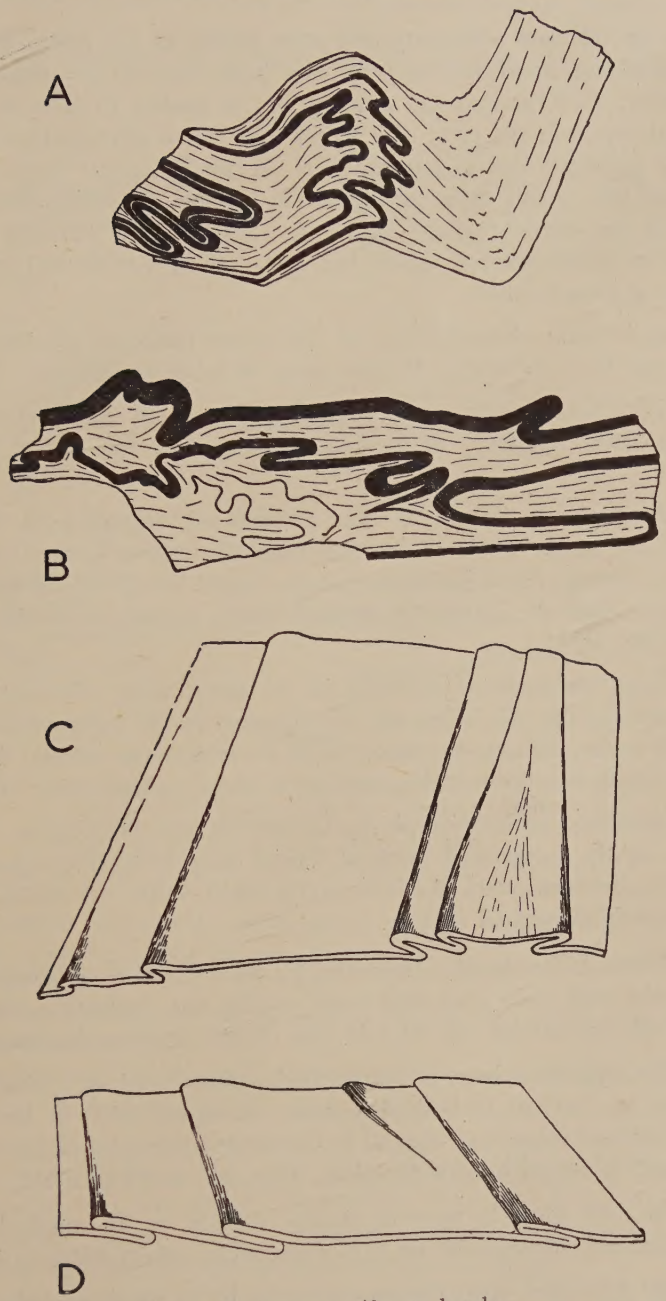

FIG. 1.—Fold structures in the garnetiferous bands.
A. Compressed folds (second class) with superimposed later buckling effects. Glenmalure, Co. Wicklow.
B, C, and D. Compressed folds (first class). B from Luggala; C and D from Glendalough, Co. Wicklow.
Camera lucida drawings. x ½.

In a second class schistosity and axial planes of the minor folds correspond in orientation and stand vertically or at a high angle to the stratification of the bedded series: their mechanical arrangement is similar to that of drag folds in incompetent layers in the crest of a larger fold where stratification and schistosity lie broadly perpendicular to one another. It would appear from these relations that folds of the second class correspond in location to major fold arches in the structure of the district: those of the first class would similarly represent the position of the large-scale fold limbs (Fig. 5 A). Such a structural arrangement can be observed at some localities.

The main form characteristics of the minor folds are illustrated by typical examples, and their distinctive features may be listed as follows:

(1) The folded bands are original sedimentary strata, homogeneous in composition, and commonly of regular thickness over the folded portion of the layer.

(2) A dominant feature is their pronounced flattening in the schistosity direction of the rock. Folds of the first class thus show marked assymmetry of form, and in strongly developed examples the crestal bends of folds may be scarcely distinguishable, and the extremely attenuate limbs appear as normal parallel beds in the schist (Pl. 15 A).

(3) Folds are enclosed smoothly in the surrounding schistosity so that the elaborate forms of the grit layers are not repeated in the adjacent mica-schist. In this way, due to the disharmonic behaviour of the intervening schists, the undulations of adjacent bands may show little similarity in detail to each other (Fig. 1 B).

(4) Individual folds are typically of very slender proportions, with rounded arches and tightly compressed isoclinal limbs: they frequently appear in closely packed groups between which the intervening schist septae are highly attenuate or almost completely eliminated.

(5) Where thicker bands—upwards of 2 cm.—occur in association, they often show a simpler and more open fold form, in this way indicating an approximate agreement with the Sander rule of fold size (Regel der Stauchfaltengrösse).

(6) The structures have a complicated pattern, and in a single layer folds may be seen to overturn in both directions. Complex folds in two directions—giving an 'Omega' form—are seen to be developed from simple isoclinal folds by a flattening-out in the schistosity direction. (Fig. 1 C and Fig. 2 D).

(7) The fold form is seen to change rapidly in an axial direction, and individual folds may likewise die out to be replaced by others within a short distance.

Adjacent fold axes often diverge mutually by as much as 90° and the crest lines show a strongly curved form.

(8) Involution effects are seen where adjacent layers—tightly packed together—have produced a distortion of the folds against each other. A similar

effect results from superposition of later folds on a tightly compressed fold series (Fig. 1 A).

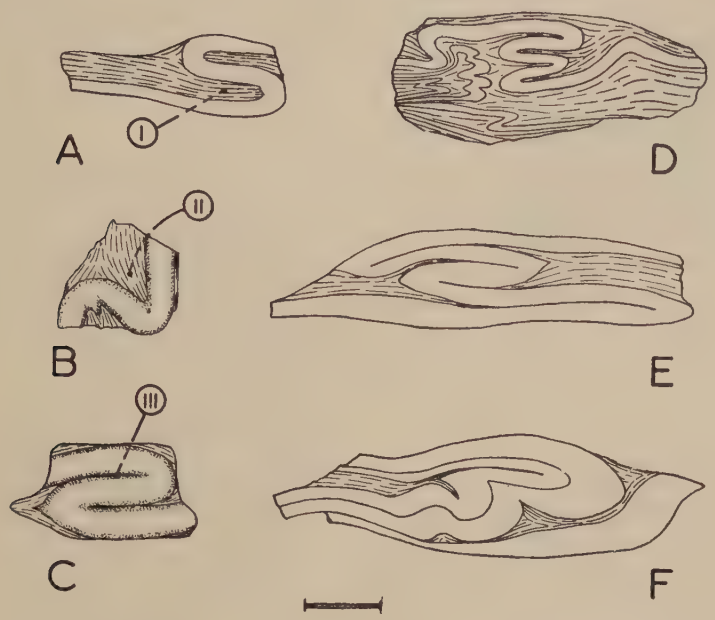

FIG. 2.—Fold details. Camera lucida drawings. The scale represents 2 cm. A. B. D, Glendalough. C, Rathmichael, Co. Dublin. E, F, Glenmacnass, Co. Wicklow. (i, ii, iii, represent locations of micro-sections shown in Plate 14.)

(9) Thickness variations, where locally present in the folded beds, are seen to be a result of the following causes:—

(a) Plastic deformation of contiguous layers by compaction against one another, as mentioned in (8).

(b) Attentuation of unfolded portions of the siliceous layers in association with movements of the more plastic schists around. In folds of the first class this effect may be seen in a thinning-out of the layer between separated folds (Fig. 1 C): it often extends also to the outer limbs of tight 'S'-folds, so that the inner, or reversed, limb may appear notably thicker than other parts of the band (Fig. 3 B). This is a significant feature, quite in contrast to the common attentuation of the reversed limb of an overfold under normal folding conditions.

Conversely, in the second class of folds, a thinning of the fold limbs is often accompanied by relative thickening of the fold arches, and is associated with schistosity movements: it is noted that in this case there is a general correspondence between fold forms in adjacent grit layers. The relations observed are similar to those developed in common shear folding.

(c) Occasionally a general plastic deformation within the siliceous beds is seen. Distortion and drawing-out of the fold crests of the small-scale structures is a typical effect, and such behaviour may ultimately lead to reduction of the fold bundles to the form of smooth lenticular bulges or nodes, each containing a single, almost obliterated, groups of folds (Fig. 3 A). A series of similar examples of plastic deformation effects is illustrated by Quirke and Lacey from the crystalline pre-Cambrian rocks of Canada (1941, Fig. 3).

In the case of the thicker quartzite beds—the normal siliceous types of the Lower Palaeozoic sedimentary series—which range upwards from 2 cm. to several feet in thickness, the deformation structures are of a rather different nature. In thinner layers of this type, minor folds are developed which approach closely the compressed ribbons of the garnetiferous rock in form and dimensions (Fig. 3 B), but, in general, these stronger beds are distinguished by more open, smoothly-curved folds, and contortions with normal proportions.

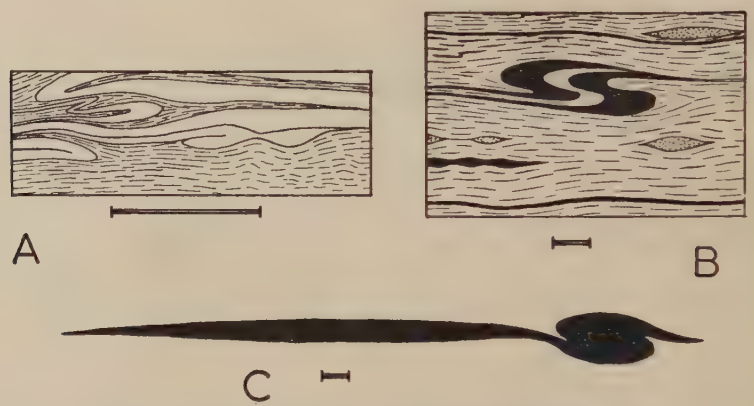

Fig. 3.—Plastic deformation effects in the siliceous layers.
A. Camera lucida drawing of fine-grained garnetiferous bands. Glendalough. B, C. Field sketches of normal white quartzite layers (black) and quartz segregation lenses (stippled): the various structures are contemporary and have a similar orientation. North side of Scalp, Co. Dublin. The scale in each case represents 2 cm.

Plastic deformation within the psammitic layer, rather than folding, is a dominant feature, and the beds repeatedly pinch and swell in thickness, leading in places to the development of an irregular noded effect: pinch-outs are sometimes seen though ruptural effects do not often occur (Fig. 3 C). Such noded forms, both in the deformed quartzite bands and in associated segregation quartz lenses, are found to have a dimensional orientation in line with the fold structures.

A small-scale example of deformation in the siliceous rocks (Fig. 4 A) from the Mount Pelier district—though it comes from the western flank of the granite mass—is of interest, since it illustrates clearly the paracrystalline nature of the

movements and the high degree of plasticity achieved in the material during metamorphic recrystallisation. It features a folded quartz-andalusite segregation vein, developed concordantly in a series of finely-banded siliceous biotite-hornfels layers. Large pink andalusite crystals, clustered along the walls of the vein, have been

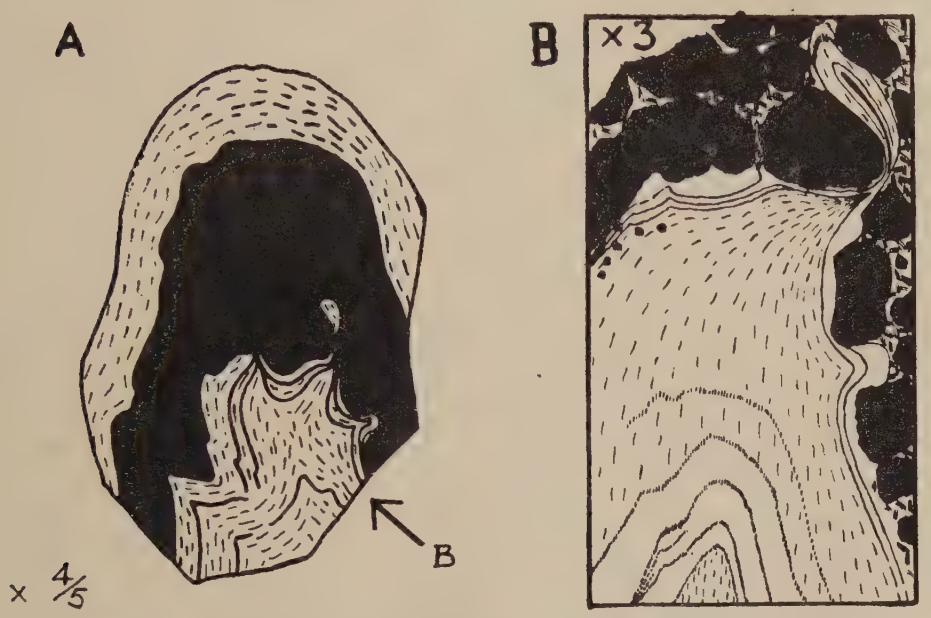

FIG. 4.—A. Folded quartz-andalusite vein in siliceous biotite-hornfels. Mount Pelier Hill, Co. Dublin. B. Detail from A, above, showing plastic squeezing of banded siliceous layer between large andalusite crystals (black) at margin of vein.

affected by the paracrystalline movements, and in some instances are broken down to groups of scattered and optically disorientated fragments in the quartz mosaic of the vein. At the vein border, on the inner surface of the fold, the siliceous layers form smooth undulations around the large crystals and are kneaded-on to the andalusites in a remarkable manner. They locally show diapir-like injections between large crystals of this mineral, which may take the form of a smoothly flowing masses of the hornfels, almost detached from their origin (Fig. 4 B): the squeezed-in body thus formed retains its characteristic texture and primary striping, though the fine bands are distorted and vary in thickness in the manner of flow-folds. It is evident that the small-scale movements, which post-date the formation of the andalusites, were here an accompaniment to the folding of the vein. The plastic deformation in the siliceous rock was achieved by operation of intergranular partial movements, and it clearly—since the adjacent andalusite prisms have not been deformed at their contacts with the injected mass—must at that stage have possessed a high degree of mobility.

It remains to examine the mechanical behaviour of the soft pelitic rocks of the aureole, in which the siliceous beds occur as minor intercalations. In an earlier note (1948) it has been indicated that intrusion of the granite at its northern end took place to the accompaniment of thorough-going deformation in the rocks of the metamorphic aureole: as a result, the prevailing mica-schists show a general development of paracrystalline mineral textures. The characteristic type is a silvery muscovite-schist, comprising a perfectly aligned felt of white mica, with subsidiary scales of ilmenite and associated quartz and tourmaline: porphyroblastic crystals of the typical metamorphic minerals are scattered through the ground-mass of the rock.

A thin section through the crest of one of the more open folds shows that in the fold arches a gradual transposition of the original schistosity of the pelite takes place, with the initial development of tiny micro-folds framed by polygonal arches of undistorted mica plates: these structures have the character of similar folds, with axial planes parallel to, or diverging slightly from, the axial plane of the main structure (Pl. 15 B). The more open polyhedral arches and S. folds in the schist (Pl. 15 E) are seen to be transitional to sharply V-shaped forms, and these, with development of more acute outlines, pass into continuous laminage zones which replace their fold limbs: alternate zones are composed of parallel groups of mica plates and lie slightly oblique to one another.

Further deformation of the schist, when the siliceous band has assumed compressed isoclinal proportions, shows the shear zones of parallel undeformed mica plates progressively extended at the expense of fold structures, and its main fabric now lies in this direction (Pl. 15 C): only minor areas of the early structure remain as scattered relics through it, most commonly in the form of incomplete or partial fold limbs represented only by narrow sheafs of oblique-lying mica plates. At this stage the schist septum is reduced to a fraction of its former dimensions, and with the development of a new and nearly perfect schistosity in the axial plane direction further thinning-out is apparently by pervasive plastic deformation and intergranular adjustments in its fabric.

At the final stage, only a thin film of aligned mica flakes may remain between the tightly appressed limbs of the garnetiferous layer (Pl. 15 D). In this way it is seen that during the tight folding of the psammitic beds, the associated schist is progressively removed by plastic migration from the fold arches, and with the transposition of its original schistosity in the vicinity of the folds these structures come to lie smoothly enclosed as compact fold clusters in the schists. As is indicated by details of the schist fabric and by other features, the deformation is of a paracrystalline nature.

Discussion of the Folding Mechanism.

It is apparent from their relation to paracrystalline movement features that the fold structures have arisen in connection with a deformation which accompanied

intrusion of the granite body, and operated during the recrystallisation of the aureole rocks. In spite of a certain resemblance in form to slump folds and other contemporaneous deformation effects in unconsolidated sediments, such as are extensively developed in the Lower Palaeozoic geosynclinal series generally, there can be little question of a confusion with such features, and it is shown that the present structures are purely tectonic in origin. For example, in the case of preserved sedimentary structures the fold interspaces would be essentially protected and unmoved areas during metamorphism, and should therefore be represented by patches showing hornfels texture: in the present instances, the mechanically-formed schist penetrates between the slender fold limbs as narrow septae and is itself connected with the folding deformation. Also, the fold structures clearly precede the later stages (Stages II and III) in the metamorphic history of the rocks, and, in fact, compound fold effects due to operation of late movements on the compressed ribbon folds are easily recognisable.

From the characteristics tabulated in the preceding section, and so distinctive of these structures, it is seen that the elaborate, and often involute, folding cannot be explained by ordinary, flexural processes—buckling or bending (due to lateral or vertical stresses, respectively), shear folding, or flow folding. The folded beds are not internally deformed in their texture or broken-up rupturally by the movement effects, and the essentially non-directional aspect of the undulations precludes their formation by a real directed stress. It is evident that the layers have behaved in a passive manner so as to deform smoothly and continuously throughout the folding process.

It is also apparent that the dominant alignment of the folds with the schistosity, and their pronounced flattening and compaction in this direction, indicate that the mechanical effects producing this schistosity were a controlling factor in the fold development. We may conclude, therefore, that the mechanism was an " all-sided " or virtually hydrostatic effect in the surrounding schists under the conditions of contact-metamorphism—a hypothesis to which the continuous nature of the bands, the general absence of thickness variations, the tightly appressed arches, and the involution of contiguous folds all lend support. It is considered, therefore, that the ribbon-like folds owe their development to disharmonic flow of the enclosing schist, which has migrated from between flexures in the alternating siliceous layers so that the latter are compressed into tightly packed, flat-lying folds in the schistosity of the pelite. The forms which thus arise are controlled by the thickness of the folded layer, and the distinctive ribbon folds are confined to bands ranging up to about 2 cm.: beyond this range the thicker psammitic beds show other fold forms. These processes are strictly in harmony with the plastic deformation effects revealed in the more homogeneous pelitic rocks of the aureole, and demonstrate that conditions of extreme mobility obtained during the contact metamorphism.

It has been shown experimentally by Keunen (1938) in studies concerning the formation of ptygmatic folds that, in a more competent layer surrounded by a

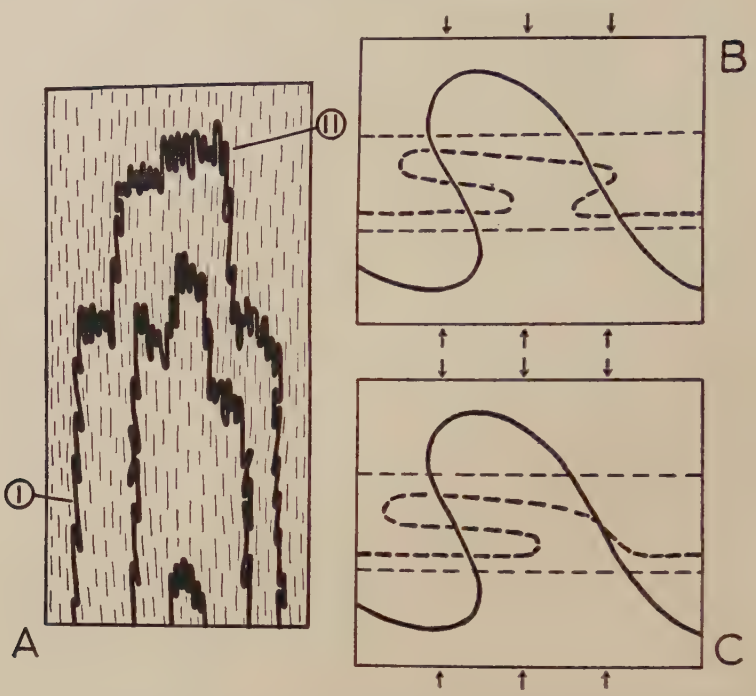

FIG. 5.—A. Diagram showing relations between schistosity and folds of the first (i) and second (ii) classes in the garnetiferous bands. As observed at Luggala, Co. Wicklow. B. Deformation mechanism in the development of the compressed folds.

FIG. 6.—Fold forms in the Riedal Salt Mine, Germany—showing sylvite band (black) between Older Rock Salt (Naä) and Younger Rock Salt (Naj) Series. After Hartwig (1937).

weaker medium, highly elaborate folds with a form closely similar to those here described may be produced by a pressure acting on the mass generally, in line with the direction of the layer. In the enclosing weak material the resultant is essentially a hydrostatic stress, and the deformation is seen to involve its plastic flow and migration from fold arches which develop in the stronger band so as to allow them to close in acute forms. It will be seen that, in the case of the Leinster garnetiferous bands, the structural conditions which prevail in fold structures of the second class are of analogous character, and the mechanical procedure was evidently the same. Here schistosity of the enclosing pelite is the controlling feature and is arranged perpendicular to the more rigid siliceous layers: lateral compression of the deformed mass has resulted in a folding of these layers, and with pervasive flow movements in the schistosity of the surroundings they gradually become compressed into elaborate forms orientated to this direction.

Th. Vogt (1927, p. 164) has made use of a generally similar mechanism to explain compressed and highly attenuate folds in a banded series of metamorphic sediments associated with the syntectonic phacoliths of northern Norway. Quirke (1931, Fig. 3) also illustrates a comparable case where compressed folds have developed in a strong layer, as a result of plastic deformation of enclosing marble.

But it is clearly evident that this mechanism is not capable of the initial production of such folds in a layer placed perpendicular to the general direction of pressure: it fails to provide a complete analogy for the compressed folds of the first class. In this case it must be considered that the structures existed as folds before the plastic movements in question became operative, and they presumably arose as a result of a normal folding process: in this case, the compressed fold form is therefore, strictly speaking, a secondary feature superimposed on earlier undulations. Their manner of formation is represented in Fig. 5 B. This explanation is readily acceptable on examination of examples such as Figs. 1 C and D, where the arrangement of the small-scale structures is highly suggestive of a development from original sets of minor drag-folds by subsequent intervention of disharmonic flow in the surroundings.

Salt-dome tectonics provides many examples of structures closely comparable to those here described, of which the mechanics is well authenticated. Fig. 6 from the Riedal Salt Mine shows a typical German example in which the closely appressed flexures can be clearly seen. Here the underlying Older Rock-salt Series has risen disharmonically under an essentially hydrostatic pressure, in an outer cover of the Younger Rock-salt: the persistent intervening layers of sylvite —more competent than the surroundings—have taken on intense undulations as a result of this disharmonic plastic flow.

Summary and Conclusions.

A series of garnetiferous psammitic layers, which appear persistently as minor intercalations in the metamorphic Lower Palaeozoic sediments along the eastern

margin of the Leinster Granite, are shown to represent original strata of the character of manganiferous sedimentary ironstones. As a result of the contact-metamorphic effects, their essential mineral constituents are spessartine-almandine garnet and quartz, with some iron and manganese oxide. Corresponding occurrences from the Lower Palaeozoic of Wales and of Central Europe are compared, and it is shown that in composition the materials correspond most closely to carbonate-free siliceous ironstone formations. A primary iron silicate mineral was probably present in the original sediment.

As regards their structural features, these layers show remarkable small-scale effects developed during intrusion of the granite by paracrystalline deformation in the aureole rocks. Analysis of their behaviour is essentially a study of the deformation mechanics of a mixed rock series involving minor intercalations of more rigid material—the psammitic beds—enclosed within soft pelitic formations—the Killiney-type mica-schists, and forms developed are a result of disharmonic movements between these two media. It is indicated that the development of the distinctive compressed folds is controlled by the thickness of the layers—they fall within the approximate limits 0·1 to 2·0 cm.—which range essentially comprises the garnetiferous beds in the series. Close analogies are shown, on one hand, to experimental results produced with comparable materials, and on the other hand, to the much-studied salt-tectonics effects, where, in very different materials, similar mechanical conditions are known to have obtained. Thicker psammitic bands behave in a different fashion—by folding of a more open and less regular type, or by continuous plastic deformation within the bed, leading to variation in its thickness.

These general effects clearly illustrate the high degree of plasticity achieved within the aureole during the granite intrusion: it is evident that in the case of typical examples of the compressed folds a local displacement of the pelitic material of remarkable magnitude must have been involved (Fig. 5 B and C). Acting in co-operation with corresponding effects in the soft pelitic mica-schists the phenomenon would appear to have resulted in large-scale plastic deformation throughout the aureole, and we may in this way consider the belt of contact—metamorphic rocks surrounding the Leinster granite as of the nature of a mobile envelope to the igneous mass during its intrusion.

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Explanation of Plate 15.

A.—Tightly compressed complex folding of garnetiferous bands in schist with weaker subsequent crumpling superimposed. A horizontal surface showing NE-SW trending schistosity which dips at low angles to the south-east. The compressed folds are seen to pitch due east (90° bearing) and thus lie oblique to the main structural trend. A razor blade gives the approximate scale. North slopes of Rathmichael Hill, Co. Dublin.

B. C. D. Photomicrographs of fold structures showing progressive deformation stages of the pelitic material in the core of the folds.

B.—Small-scale microfolds of polygonal outline passing into zones of laminage in their flank areas. (ii in Fig. 2B). x 6. Glendalough.

C.—Portion of tight S-fold with isoclinal limbs showing attenuated schist septum, in which parallel zones of micas, aligned to the main fold axis, replace the earlier microfolds, leading to the development of a new, transposed, schistosity in line with the main fold axis. Tension cracks developed perpendicular to the walls of the psammitic band during folding, and later filled-in by quartz, radiate from the fold crest and are just distinguishable. (*i* in Fig. 2A). x 6. Glendalough.

D.—Typical garnetiferous band, showing portion of a tight S-fold: textural changes towards its margin are attributable to metamorphic diffusion effects. A thin, indefinite, band of aligned muscovites near the centre of the field is all that remains of the original schist septum. (*iii* in Fig. 2C). x 12. Rathmichael.

E.—Portion of B above, enlarged to show textural details of the schist—relic microfolds with polygonal or acute V-shaped arches, and laminage zones—in this case with pre-crystalline characteristics. x about 70.

FIG. A.

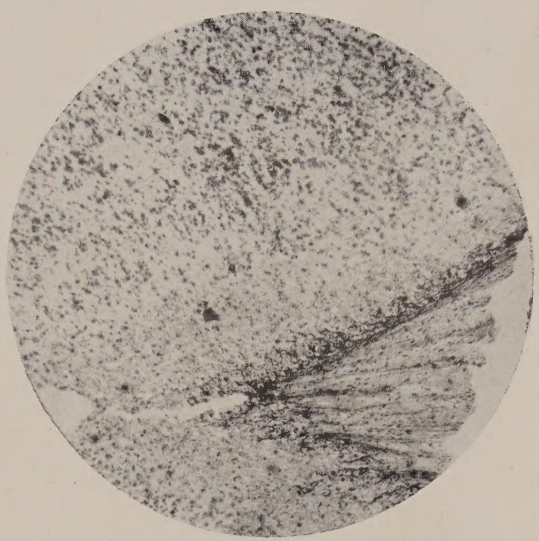

FIG. B.

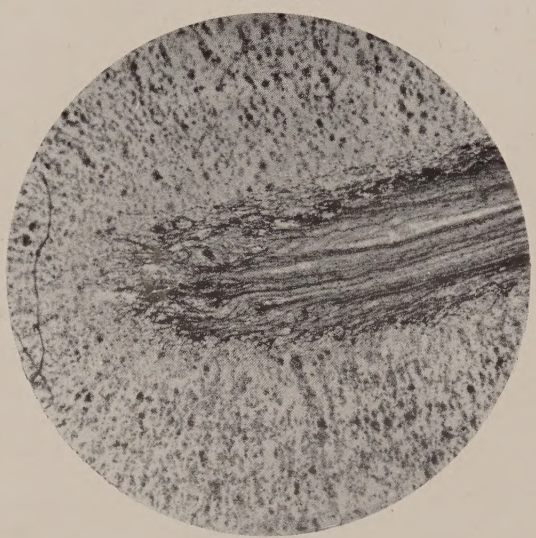

FIG. C.

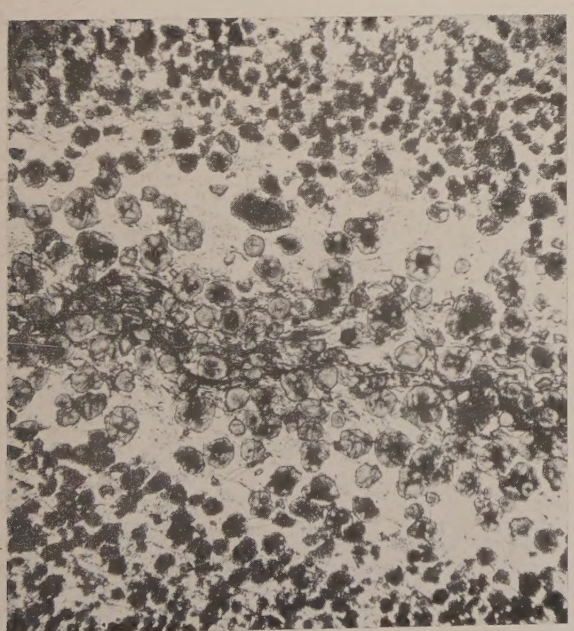

FIG. D.

FIG. E.